The 10G TTC-PON: Challenges, Solutions and Performance

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on behalf of the TTC-PON team
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Outline

• Introduction to TTC-PON

• System Challenges & Solutions

• TTC-PON Core

• Conclusions

• Potential Developments for Phase-2
Current TTC System

- TTC = Timing, Trigger and Control
  - Designed in ~2000
- Unidirectional system (optical) / 1310nm
- 1:32 split ratio maximum
- Low bandwidth: 80Mb/s
- Busy/throttle on a separate link

Too limited for phase1/2 upgrades
PON Basics

- PON = Passive Optical Network
  - Used in FTTH
- Point to Multipoint Network (P2M)
  - Bidirectional / WDM: 1 fiber, 2 wavelengths (1 Up, 1 Down)
- Downstream (OLT->ONU)
  - High bandwidth
- Upstream (ONU->OLT)
  - Low & shared bandwidth
  - Arbitrated by OLT

OLT=Optical Line Terminal
ONU=Optical Network Unit
TTC-PON System

- Previous work: [1], [2], [3]
Downstream path

- OLT → ONUs (continuous transmission)
- 9.6Gbps serial link (240 raw bits per BC / 8b header, 24b – control)
- LHC Bunch Clock (BC) synchronous
- Fixed & Low latency
- High bandwidth

10G PON-TTC

- Bunch clock period (25ns)
- 240 bits

* Not in scale
Downstream path

- Challenges:
  - PON Standard line rate close multiple of 40MHz
    \[ \Rightarrow \text{XGPON (9.8Gbps} \rightarrow \text{TTC-PON} \rightarrow 9.6\text{Gbps)} \]
  - Deterministic latency
    \[ \Rightarrow \text{Careful choice PLL} \]
    \[ \Rightarrow \text{FPGA transceiver buffer bypass} \]
    \[ \Rightarrow \text{Recovered clock alignment to header} \]
  - Small optical margin with simple 8b10b
    \[ \Rightarrow \text{Scrambling + FEC (Forward Error Correction)} \]
    \[ \Rightarrow \text{Target margin} \approx 3\text{dB} \text{ (conservative approach)} \]

For 100m fiber

Power Budget=22.88dB
MARGIN=1.33 dB

For 100m fiber

Attenuation (dB)

- 1:64
- 1:32
- 1:16

connectors

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Errors observed seem to have random nature (different from GBT environment)

- Binary BCH codes are good for correcting random errors with a relatively low complexity [5]
  - Systematic encoding: BCH(n,k)
- Four shortened-BCH codes were evaluated:
  - BCH(40,34)
  - BCH(80,73)
  - BCH(120,113)
  - BCH(120,106)
- Main Figures of merit:
  - Efficiency (k/n)
  - Coding gain
  - Latency
  - Timing
  - Complexity (area)

- Scrambling: signal randomizer
  - Self-synchronous scrambling: no sync. overhead but error multiplication...
Downstream path

- Decoder parameters considered for latency, slice luts and timing slack on Kintex7

* RS(15,11) can correct two four-bit symbols

Measurements Results:

![Graph showing Measured FEC - Coding Gain](image)

- **GBT-RS(15,11)** - EFF=73.33%
- **BCH(120,106)** - EFF=88.33%
- **BCH(120,113)** - EFF=94.17%
- **BCH(80,73)** - EFF=91.25%
- **BCH(40,34)** - EFF=85.00%
- Uncoded
- Spec

![3D graph showing Efficiency, Slice LUTs, Coding Gain, Timing Slack, and Frame Latency Overhead](image)
## Downstream path

- **Summary:**

<table>
<thead>
<tr>
<th>Encoding scheme</th>
<th>8b10b</th>
<th>FEC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line-Rate</strong></td>
<td>9.6Gbps – sync. to bunch clock</td>
<td></td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>Fixed and deterministic [4] (value to be characterised with FEC)</td>
<td></td>
</tr>
<tr>
<td><strong>Power Budget</strong></td>
<td>22.88dB (8b10b)</td>
<td>~25.05dB (worst-case BCH(120,113))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~26.22dB (best-case BCH(120,106))</td>
</tr>
<tr>
<td><strong>User payload</strong></td>
<td>160b (8b10b)</td>
<td>172b (worst-case BCH(40,34))</td>
</tr>
<tr>
<td>(per bunch-clock)</td>
<td></td>
<td>192b (best-case BCH(120,113))</td>
</tr>
</tbody>
</table>
Upstream path

- ONUss -> OLT (time-division multiplexing)
- 2.4Gbps link - 8b10b encoded

! Minimize Waiting Time:
Number_ONU \times \text{Burst length}
A word on upstream overhead:

- Burst-mode receiver difficulties: large dynamic range / short settling time

- A reset signal between bursts is needed in order to start threshold extraction

* XGPON specs:
  - Minimum Gap: 25ns
  - Minimum Reset Pulse Width: 25ns
  - Maximum Setting time: 52ns (=minimum preamble length)
Upstream path

- Burst composition: 125ns long

<table>
<thead>
<tr>
<th>Component</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap</td>
<td>25ns</td>
</tr>
<tr>
<td>Preamble</td>
<td>58.3ns</td>
</tr>
<tr>
<td>Comma + Addr</td>
<td>8.3ns</td>
</tr>
<tr>
<td>Payload</td>
<td>33.3ns</td>
</tr>
<tr>
<td>Payload (64b-16b ctrl + 48b user)</td>
<td>33.3ns</td>
</tr>
<tr>
<td>Total Gap+Burst</td>
<td>125ns</td>
</tr>
<tr>
<td>Latency (64 ONUs)</td>
<td>64x125ns=8us</td>
</tr>
<tr>
<td>Average data-rate (64 ONUs)</td>
<td>8Mbps (64b/8us)</td>
</tr>
</tbody>
</table>

Busy waiting time
Upstream path

- Challenges:
  - Link synchronization
    ⇒ Clock recovery and re-use for transmit path with controlled phase (@ONU level)
  - Phase changing between bursts → classical CDR is not an option
    ⇒ Oversampling scheme (@ OLT RX level)
  - TDM arbitration (token is automatically passed between ONUs)
    ⇒ Requires a calibration procedure
Upstream path

- Oversampling
  - Zero time-to-lock
Upstream path

- TDM arbitration
  - OLT broadcast TIME REFERENCE SIGNAL (HEARTBEAT)
  - HEARTBEAT PERIOD = Number_ONUs x 125 ns
  - Each ONU has an internal counter + defined offset to transmit
Upstream path

- TDM arbitration – Calibration
  - The procedure is arbitrated by the master (OLT)
  - OLT measures the roundtrip time for each ONU:
    - Each ONU transmits continuously during calibration (while others are OFF)

- OLT offset in TDM is compensated
  - Timing resolution can be up to 1UI=0.416ns

=> During run, gap can vary between 25-0.416 ns and 25+0.416 ns
Upstream path

- **Power Budget**

  - Target BER: $10^{-11}$ - CL: 0.95 – ≈10 days measurement

  - Comfortable margin
Upstream path

- Dynamic range
  - No penalty up to 12 dB

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**oni1**

- LOUD - DR=0dB
- LOUD - DR=3dB
- LOUD - DR=6dB
- LOUD - DR=9dB
- LOUD - DR=12dB

**oni2**

- SOFT - DR=0dB
- SOFT - DR=3dB
- SOFT - DR=6dB
- SOFT - DR=9dB
- SOFT - DR=12dB

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TTC-PON Core - firmware

- Core design
  - Similar structure for OLT/ONU
  - Currently implemented in Kintex7
  - Fully software configurable
  - Firmware started being delivered to users (collecting feedback)

* ONU can be also controlled via OLT
Conclusions

- Simple FEC scheme could allow us gaining in power budget in order to have a safe optical margin (for 1:64 ONUs) and have a higher efficiency in downstream.

- Stable upstream protocol relying on 125ns bursts was depicted.

- First version of TTC-PON core IP is being delivered (collecting feedback).

- Next steps:
  - Migration to other FPGA families – Kintex Ultrascale, Arria10.
  - Long BER tests.
  - Temperature tests on OLT/ONU and Si5344.
  - Investigate new PON standards.
Potential developments for Phase-2

- Xilinx BCDR evaluation
  - Burst Clock Data Recovery for 1.25G/2.5G PON Applications in UltraScale Devices
  - Burst-Mode Clock Data Recovery with GTH and GTY Transceivers

- NGPON2
  - WDM and coloured ONUs

- XGS PON
  - Symmetric 10G PON (intermediate step between GPON and NG-PON2)
Thank You!
References


TTC-PON - Setup

Downstream
1577nm
9.6Gbps

Upstream
1270nm
2.4Gbps
TTC-PON – Downstream FEC

- BCH decoder – target low latency:

  - Single error-correcting
  - Double error-correcting

* = operations in GF(2^7)
TTC-PON – Downstream FEC

- Scrambling
  - Ex: $x^{43} + 1$
## TTC-PON – Upstream burst length

- Burst length: 33ns x 125ns

<table>
<thead>
<tr>
<th></th>
<th>33ns burst</th>
<th>125ns burst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap+Preamble</td>
<td>16.6ns</td>
<td>83.3 ns (datasheet = 77.2ns)</td>
</tr>
<tr>
<td>Comma+Addr</td>
<td>8.3ns</td>
<td>8.3ns</td>
</tr>
<tr>
<td>Payload</td>
<td>8.3ns (16b)</td>
<td>33.3ns (64b)</td>
</tr>
<tr>
<td>Latency (64 onu’s)</td>
<td>2.1us</td>
<td>8us</td>
</tr>
<tr>
<td>Average data-rate</td>
<td>7.6Mbps (16b/2.1us)</td>
<td>8Mbps (64b/8us)</td>
</tr>
<tr>
<td>APC</td>
<td>Modified</td>
<td>Normal (Er≈5.4dB)</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>~ 1.0dB</td>
<td>No penalty for 6dB spec</td>
</tr>
<tr>
<td>Temperature</td>
<td>Huge impact from 45°C</td>
<td>Tested up to 55°C – no impact</td>
</tr>
<tr>
<td>Sensitivity@1e-11 (OMA)</td>
<td>~ -24 dBm</td>
<td>~ -24 dBm</td>
</tr>
</tbody>
</table>
TTC-PON – Resources & Costs

Resource & Costing...

- Resources (of a middle range Kintex 7):
  - OLT =~ 1% Slices LUT
  - ONU =~ 0.5% Slices LUT

- Cost (unit price – buying 10 components)
  - SFP+ OLT: 965 USD / 667 USD
  - XFP+ OLT: 1075 USD / 667 USD
  - SFP+ ONU: 258 USD / 105 USD